MONTHLY WEATHER REVIEW

Editor, EDGAR W. WOOLARD

VOL. 70, No. 2
W. B. No. 1350

FEBRUARY 1942

CLOSED APRIL 3, 1942
ISSUED MAY 14, 1942

OBSERVATIONS OF RADIATION PENETRATION THROUGH SNOW

By IRVING F. HAND and ROY E. LUNDQUIST

[U. S. Weather Bureau Solar Radiation Station, Blue Hill Observatory, and U. S. Weather Bureau, Salt Lake City, September 1941]

The penetration of solar radiation through various thicknesses and qualities of snow is of importance in many hydrological and other problems. Previous observations [1] of this penetration with pyrheliometric apparatus have included little if any work in the United States; and the authors therefore made some measurements at Brighton, Utah, as part of a snow project initiated in the Hydrometeorological Section of the Weather Bureau. These measurements constitute only a preliminary study, but the results have been sufficient to show the value that further work would have; data should be obtained under varying conditions of free-air temperature, height above sea-level, wind velocity, humidity, and other meteorological factors, and especially with snows of different densities and physical characteristics.

The phenomena are exceedingly complex. For example, the original loss by reflection from the snow surface nearly always exceeds the amount remaining for transmission and absorption. Considerable work has been done on the albedos, or reflection coefficients.[2] Observations of the reflection of visible radiation from snow surfaces [3] have shown that up to 89 percent of the visible radiation is reflected from clean white snow, whereas only about one-half that amount of the red component may be reflected from the same snow surface. We therefore expect a larger reflection of the visible than of the total solar radiation; numerous measurements of the latter give albedos of from 60 to about 87 percent or more under Arctic conditions.

Extensive studies have been made of the transmission of solar radiation through distilled water.[4] We may assume that fresh snow, when melted, has approximately the same characteristics as distilled water. We therefore might expect radiation absorption in snow to follow a law somewhat like that for absorption in distilled water,

$$I = I_0 e^{-kd}$$

where I_0 is the intensity of the radiation at the surface of the snow times the complement of the albedo, and I is the intensity at depth d, while k is the absorption coefficient; for snow Eckel [1] gives about 0.083 as the value of k.

The instrumental equipment used in the present study consisted of two Eppley total solar and sky radiation pyrheliometers,[5] a dual recording micromax potentiometer with full-scale deflection of 4 millivolts, a bubble sextant for obtaining the height of the sun, a portable potentiometer for checking the action of the recording apparatus, a Weston precision microammeter, and standard snow-depth and density apparatus.

A 10-junction Eppley pyrheliometer was mounted on the roof of the home occupied by Mr. and Mrs. Kenneth Shaw, cooperative observers of the Weather Bureau at Brighton, Utah, at an elevation of nearly 9,000 feet in the Wasatch Mountains, 29 miles from the center of Salt Lake City. The record from this pyrheliometer alternated every 80 seconds with the record obtained by means of a 50-junction Eppley pyrheliometer placed beneath the snow. A pit was dug in the snow with a vertical wall on one side; and in this wall the snow was scooped out, leaving a layer of predetermined thickness above the pyrheliometer, which was mounted in a horizontal position and always at the same distance from the lower side of each layer whose transmission was being studied. A large sheet of beaverboard was used as a door, with snow packed around the edges to eliminate stray light. The use of a 50-junction pyrheliometer, which gives about five-times as great an e. m. f. per gram-calory as the 10-junction, for measuring the greatly diminished intensity of the radiation after its passage through snow, in conjunction with the 10-junction for measuring the total radiation, increased the efficiency of record owing to greater utilization of the record sheet. Just prior to the readings, the recording potentiometer was checked for sensitivity by means of the portable potentiometer; and it also was checked at frequent intervals for galvanometer swing, and against the standard cell.

Preliminary measurements were made on May 14, 15, and 16, 1941, to develop a satisfactory technique of measurement; the results have not been tabulated. On the 17th, a systematic series was made, and the results are shown in table 1 and in the figure; the lower trace shows markedly the effect of lower transmission owing to ice and slush.

---

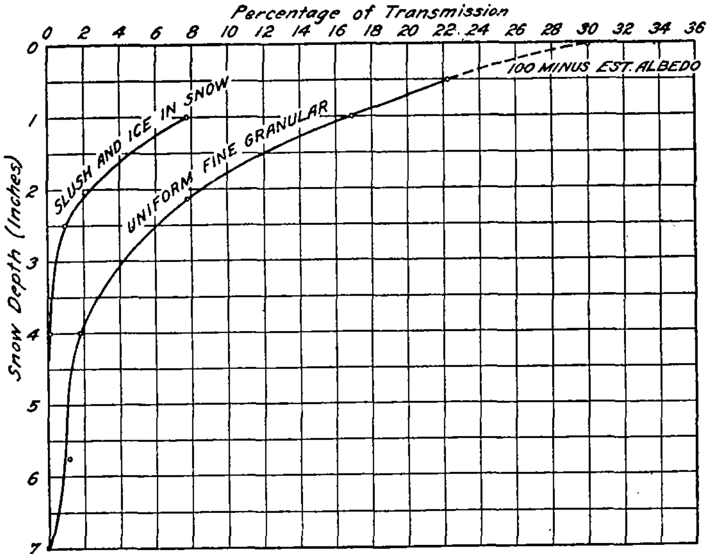
[1] See, e. g.: N. N. Kalitin, Die Strahlungseigenschaften der Schneedecke, *Gerl. Beitr. Geophys.*, 34:354–366, 1931.
Joseph Devaux, L'économie radio-thermique des champs de neige et des glaciers, *Annales de Physique*, (10), 20:5–67, 1933.
Joseph Devaux, Étude de l'Albedo de la neige dans le spectre infrarouge, *C. R.*, 200:80, 1935.
F. Steinhauser, Ein Beitrag zur Anwendung der beschreibenden Statistik in der Klimatologie, *Met. Zeit.*, 52:206–213, 1935.
Hilding Olsson, Radiation measurements on Isachsen's plateau, *Geografiska annaler*, 18:225–244, 1936.
F. Sauberer, Versuche über spektrale Messungen der Strahlungseigenschaften von Schnee und Eis mit Photoelementen, *Met. Zeit.*, 55:250–255, 1938.
C. Thams, Über die Strahlungseigenschaften der Schneedecke, *Gerl. Beitr. Geophys.*, 53:371–388, 1938.
N. N. Kalitin, *Actinometria*, Moscow, 1938.
A. A. Kuzmin, Penetration of temperature fluctuation into snow, *Meteorologia i Hydrologia*, Part 1:11–20, 1939.
O. Eckel und C. Thams, Untersuchungen über Dichte-, Temperatur-, und Strahlungsverhältnisse der Schneedecke in Davos., *Beitr. z. Geologie d. Schweiz*, Geotechn. Serie, Hydrologie, (Zurich), 1939, 273–340.

[2] N. N. Kalitin, The measurements of the albedo of a snow cover, Mo. WEA. REV., 58:59–61, 1930, see also Anders Angström, Albedo of various surfaces of ground, *Geografiska annaler*, 7:323–342, 1925. N. N. Kalitin, L'albedo spectral de la couche de neige, *Bull. Cl. sciences math. natr., Sér géogra. géophys.* No. 2–3: 153–163, 1938, Acad. Sciences, Moscow.

[3] H. H. Kimball and I. F. Hand, Reflectivity of different kinds of surfaces, Mo. WEA. REV., 57:291–295, 192?, also Mo. WEA. REV., 58: 280–282, 1930.

[4] H. R. James, with cooperation of E. H. Birge, A laboratory study of the absorption of light by lake water, *Trans. Wis. Acad. of Sci., Arts and Letters*, Vol. 31, 1938.
E. A. Birge and C. Juday, Solar radiation and inland lakes, Fourth Report, *Trans. Wis. Acad. of Sci., Arts and Letters*, 27:523–562, 1932.
C. Juday, The annual energy budget of an inland lake, *Ecology*, 21: 438–450, 1940.

[5] I. F. Hand, Review of United States Weather Bureau solar radiation investigations, Mo. WEA. REV., 65: 415–441, 1937.
B. B. Woertz and I. F. Hand, The characteristics of the Eppley pyrheliometer, Mo. WEA. REV., 69: 146–148, 1941.



PENETRATION OF SOLAR RADIATION THROUGH SNOW, BRIGHTON, UTAH

The final series of measurements in table 1 differed from the others in that freshly cut slabs were used by placing them over a recess made in a 34-inch snow pack from which the top 8 inches had been cleaned off. The recess was 6½ inches wide, 11 inches long and 8¾ inches deep, and was located in a snow-area 40 feet from the Shaw house in full exposure to the sun. Considerable difficulty was experienced in placing a ½-inch slab over the top of the recess without breakage; and should additional studies be made, the use of a glass plate of known transmission would greatly simplify the measurements. The pyrheliometer was set up at level each time for the first series of measurements and with only one setting during the next and final series. As before, great care was exercised to keep the same distance between the pyrheliometer and the lower surface of the snow, in order to minimize errors arising from internal reflections within the snow pit.

The first and greatest loss of incident solar radiation is at the surface of the snow, by reflection. A bright snow has albedo of about 87 percent, as does also glare ice; the latter seldom occurs on a snow surface. On the other hand the average reflection coefficients of wet clean and wet dirty snows are comparatively low, as shown by measurements on May 28 and 29 which gave albedos of 44 percent and 34 percent respectively. Dirty snows in and near cities have particularly low reflection and high absorption at the surface. Freshly fallen snow has an almost perfect mat surface, which results in practically identical reflection at all angles of incidence.

The results of these preliminary observations are particularly significant because the tests were conducted under conditions contributing to actual run-off. It has been observed that snow attains an average density of at least 30 percent and usually between 40 and 50 percent before any considerable run-off develops ("snow density" is used here to mean percentage of water per unit volume of snow). Snow density averaged 48 percent at the site; and snow quality for the samples tested averaged 90 percent ice grains, with 10 percent water. The fact that average snow densities do not seem to vary greatly in the process of melting during run-off periods adds to the value of these results.

TABLE 1.—*Penetration of solar radiation through snow at Brighton, Utah*

Date and time	Inches of snow penetrated	Potentiometer scale reading	Gram-calories	Total solar and sky radiation: Scale reading	Total solar and sky radiation: Gram-calories	Percentage transmission	Remarks
	Progressive thicknesses						
May 17 11:52 a. m.	10	0	0	62.2	1.493	-------	½-in. slush layer at 7 in. Fine to medium granular snow.
11:59 a. m.	4	T	T	62.5	1.499	-------	Fine granular snow ½-in. slush layer at bottom.
12:05 p. m.	2½	0.6	0.015	63.1	1.513	1.0	Fine granular snow. Before observation could be made, a ⅛ in. ice layer formed at 1¾ in. from top.
12:07 p. m.	1	4.7	.119	63.3	1.520	7.8	
12:11 p. m.	1	4.7	.119	63.3	1.520	7.8	Fine granular, but slushy.
12:16 p. m.	Mechanical and electrical zero of potentiometer checked.						
	Slab thicknesses						
12:37 p. m.	½	13.5	.342	64.3	1.532	22.3	Uniform, fine granular compact snow, average 45 percent density—from 8 to 16 in. below original snow surface—no ice or slush layers detectable.
12:43 p. m.	1	10.4	.263	64.8	1.555	16.9	
12:46 p. m.	2⅛	4.8	.121	64.7	1.553	7.8	
12:51 p. m.	4	1.1	.028	64.1	1.540	1.8	
12:55 p. m.	5¾	0.7	.018	63.2	1.518	1.2	
1:00 p. m.	7	0	0	61.8	1.485	0	

Densities near the snow surface may vary from as little as 5 percent to as much as 50 percent under the usual natural conditions on a watershed. Under the special conditions at extremely high altitudes or where snow slides produce pressure that consolidates the snow to nearly ice densities, values outside these limits may occur. Thus radiation penetration into snow layers at various seasons, and during changes in density, may be expected to vary widely. Early in our observations, it became apparent that the transmission varies with the average quality of the snow and is particularly influenced by slush or collection of melt-water, and by intermediate ice layers.

It was noted during one series of measurements that radiation passing through a layer of snow gradually decreased; examination revealed the formation of ice and slush at a definite depth. Specifically, from 12:30 to 12:36 p. m. on May 16, using snow 1 inch in thickness, an ice layer ⅛th-inch-thick formed in 6 minutes and gradually reduced transmission by 15 percent. In another instance, on May 17, during a test using initially identical snow slabs of 1-inch thickness, the radiation transmission was reduced during continued exposure of the snow layer to the sun to less than one-half the value obtained in an earlier observation, due to slush forming from melt-water. In another comparison on the same day, where 4 inches of similar fine, granular, compact snow was used for study, transmission through freshly uncovered snow of uniform texture amounted to 1.8 percent of the total solar and sky radiation, whereas after exposure to the sun for about 30 minutes the same type of snow developed a dense ¼-inch thickness of slush at the bottom of the 4-inch layer and reduced transmission to an unmeasurable value.

It may, therefore, be expected that, as snow melt increases near the surface of a firm snow pack at a rate faster than it drains away into the snow, thus forming slush and ice layers, the relative amount of radiation transmitted to greater depths will decrease.

To determine the radiation absorption effect of extraneous matter on snow surfaces, 6 circular plots 18 inches in diameter were each covered with 1 ounce of standard paint pigments. Table 2 lists the pigments used, and shows the relative effects of the various colors. The green showed an absorption nearly equal to that of the black, although the blue showed a greater drop during the first 3 days. One difficulty of this method of test was the uneven distribution of coloring matter after the first few hours. We hope to repeat the experiment under conditions which will minimize many of the errors of this first trial.

TABLE 2.—*Differential absorption tests—Standard paint pigments.*

Date and time	Depth drops in inches											
	General snow cover	Chrome yellow	Venetian red	Lamp black	Chrome green	Ultramarine blue	Orange mineral	Temperature min. max. 6 p. m.			Wind velocity	Total solar and sky radiation
May 14:								°F.	°F.	°F.	m. p. h.	gr. cal.
11:45 a. m.	0	0	0	0	0	0	0	31	52	40	3.03	------
5:40 p. m.	1	1.9	2.9	2.9	2.5	2.0	1.9	----	----	----	--------	301.0
May 15, 5:47 p. m.	3	4.8	5.6	7.8	6.8	6.9	4.3	25	48	42	2.85	584.0
May 16; 6 p. m.	7	8.5	10.2	14.0	13.1	11.0	9.1	28	55	51	3.31	------
May 18, noon	8.9	12.0	14.4	20.7	19.5	15.0	12.1	----	----	----	--------	------

NOTES AND REVIEWS

BERNHARD HAURWITZ. **Dynamic Meteorology.** New York (McGraw-Hill Book Co.), 1941. 365 pp.

It is of interest to recall that the first general treatise on meteorology to present the subject from the dynamical viewpoint was the *Lehrbuch der Meteorologie* of A. Sprung, published in 1885; this work remained the only treatise of the kind until the *Dynamische Meteorologie* by F. M. Exner, the second edition of which was published in 1925. Since the appearance of Exner's treatise, notable advances have occurred in theoretical meteorology, and encouraging progress has been made in adapting many of them to daily meteorological practice; and several books on physical and dynamical meteorology have appeared in recent years, although few are in English.

This book collects into one volume, that may be used either as a textbook or as a reference work, a comprehensive account of theoretical meteorology which includes the results of many recent investigations hitherto available only in the widely scattered periodical literature. Numerous references enable the reader to locate further details on nearly every topic; and for the benefit of the student a large number of problems are included. Insofar as any previous knowledge of meteorology is necessary, it is presupposed; and although for convenience brief recapitulations of the needed principles of physics are given, it is likewise presupposed that the reader has been trained in general physics, and in mathematics through the calculus and elementary differential equations.

After an opening chapter occupied by preliminary topics, two chapters are devoted to meteorological statics, including the adiabatic equations and theory of atmospheric stability for both dry and saturated air, and a discussion of surface pressure variations due to advection aloft. The following chapter discusses the energy of thermodynamic processes, equivalent and wet-bulb potential temperatures, convective instability and thermodynamic charts.

Chapter 5 treats the fundamental actuating factor in the physical processes of the atmosphere—solar radiation, its geographical distribution and atmospheric depletion, and the heat balance of the earth; the recent work of Elsasser and others on atmospheric water vapor absorption is included. The next two chapters are devoted to the general dynamical equations of motion of the atmosphere, the fundamental circulation theorems, and the theory of geostrophic winds and other simple types of air motion. In chapter 8, surfaces of discontinuity are discussed; and chapter 9 considers the kinematical analysis of pressure fields.

The next two chapters take up atmospheric turbulence, with its effects on the variation of wind with height and the diurnal variation of the wind, and the effect of turbulent transport of heat, water vapor, and momentum. The following chapter is devoted to the energy of atmospheric motions, and its transformation and dissipation.

The final three chapters consider, respectively, the general circulation; the perturbation method of representing atmospheric motions; and air masses, fronts, cyclones and anticyclones.

CHARLES P. OLIVIER. **Long Enduring Meteor Trains.** Publications of the University of Pennsylvania—The Flower Astronomical Observatory, Reprint No. 60.

This paper, reprinted from *Proc. Amer. Philosophical Soc.* 85: 93–135, 1942, is a catalogue of 1,336 meteor trains which either remained visible for at least 60 seconds or, if of shorter duration, showed actual drift; the catalogue tabulates the salient facts about all the trains, and a further table gives detailed data on heights and drifts for 583 of them.

The data were collected both from the immense number of original records available to the author and from a search of the published literature. The paper provides a fundamental and convenient source of existing information on the phenomena of meteor trains; and as such, it is of importance to the meteorologist interested in any problem involving the motions of the atmosphere at very high levels.